

# Chemical Enrichment of the Intergalactic Medium

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- Theoretical Framework: LCDM model
- Some recent results on CCE of the IGM
- Conclusions

# Standard LCDM Cosmological Model

- Adiabatic, scale-free, Gaussian
- Gravitational instability at work  $z=1000 \rightarrow 0$
- Universe is flat (total density = 1)
  - Baryons 5%
  - Cold Dark Matter 23%
  - Dark Energy (cosmological constant?) 72%

Consistent with:

- Inflation (not observation!)
- Light element nucleosynthesis
- Lyman alpha forest
- Clusters of galaxies and LSS at low  $z$  (BAO)
- Gravitational lensing
- $q_0$  (SNe Ia)
- $H_0$  (HST key project, SNe Ia)
- Age of the universe (stellar evolution)

$$n=0.96$$

$$\sigma_8 = 0.8$$

$$\Omega_b h^2 = 0.024$$

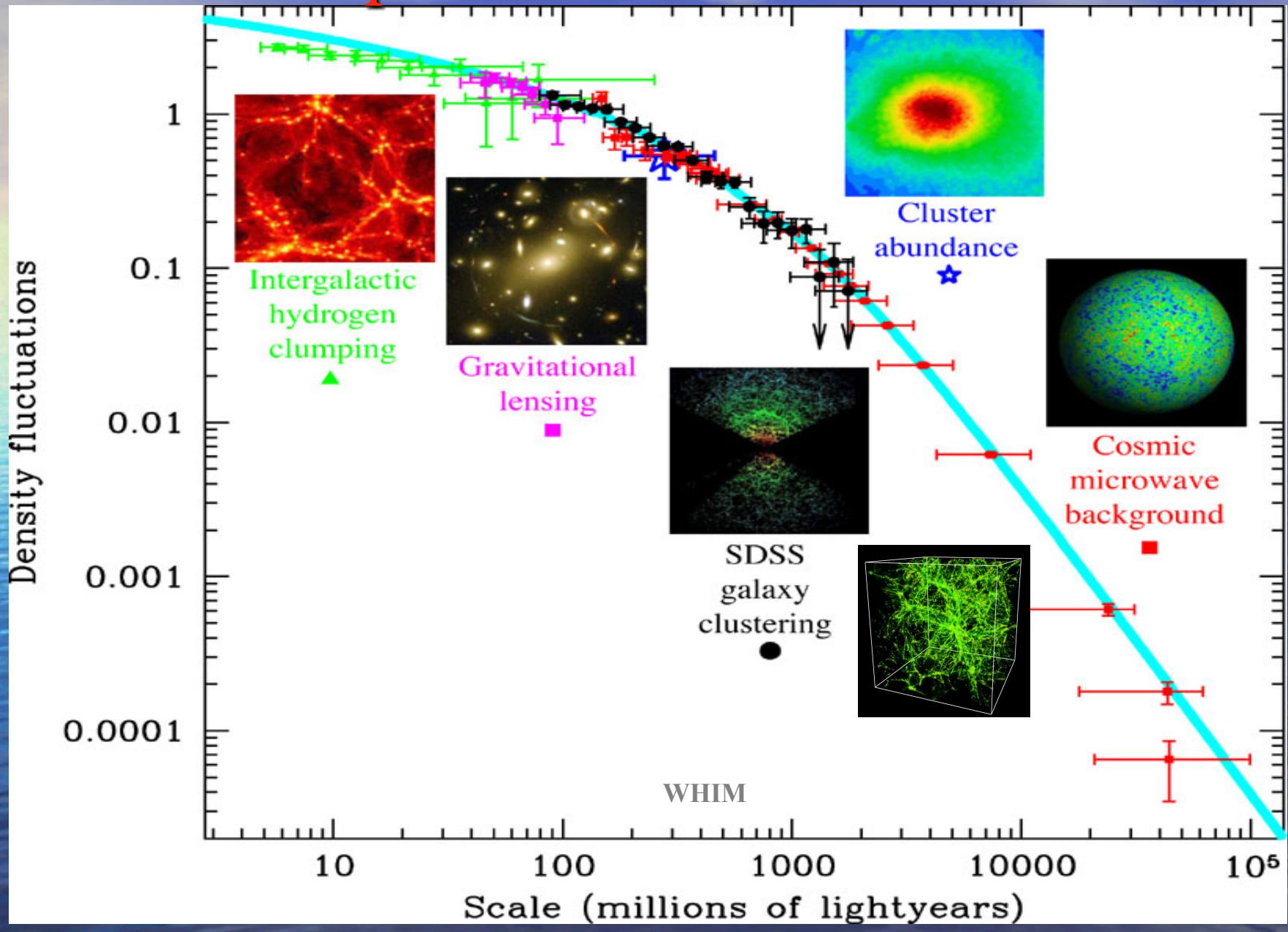
$$\Omega_x h^2 = 0.126$$

$$H_0 = 70$$

$$\Lambda = 0.72$$

Komatsu et al (2010) WMAP7

# Power Spectrum of Standard Model

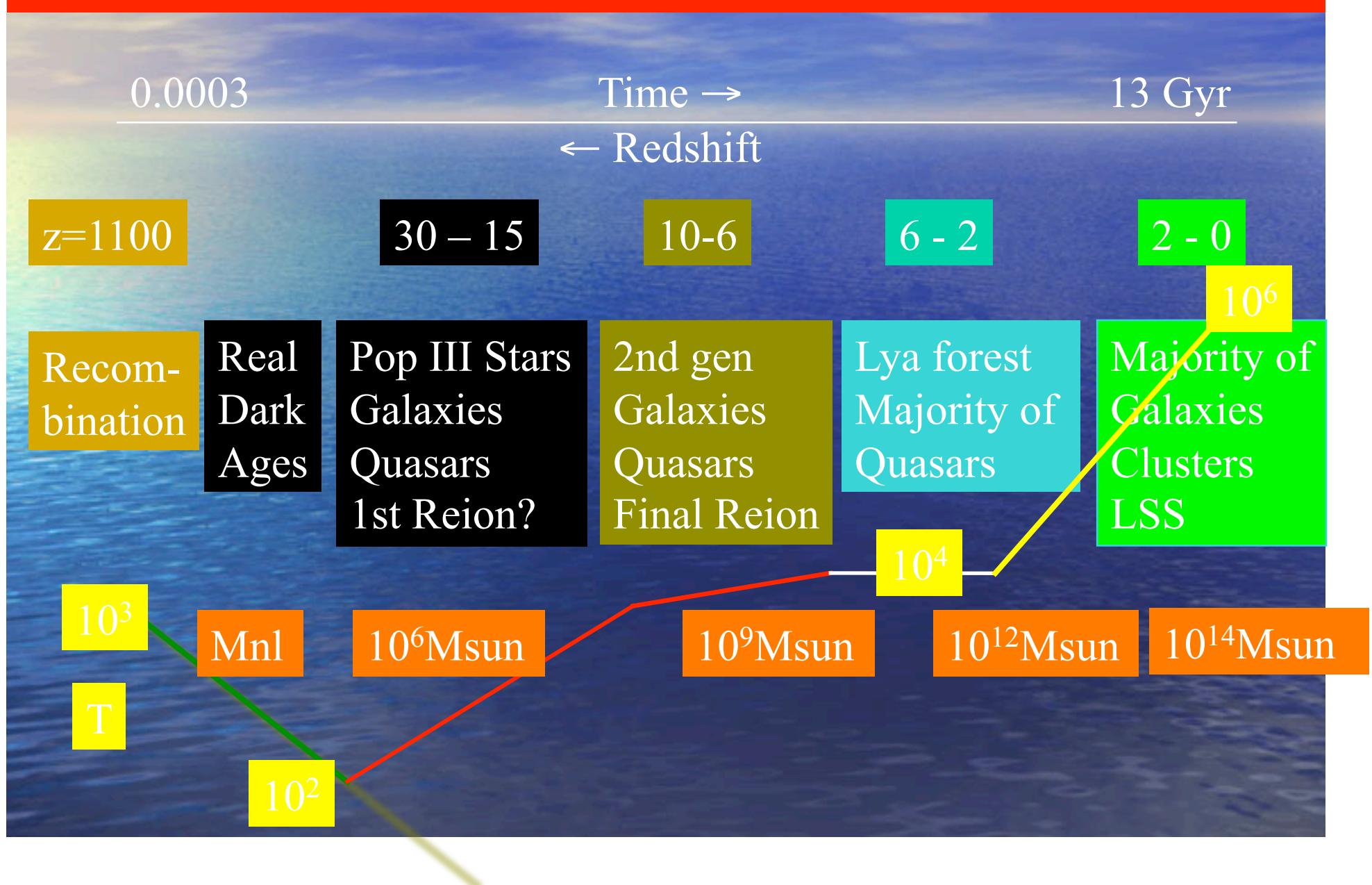


# Why IGM?

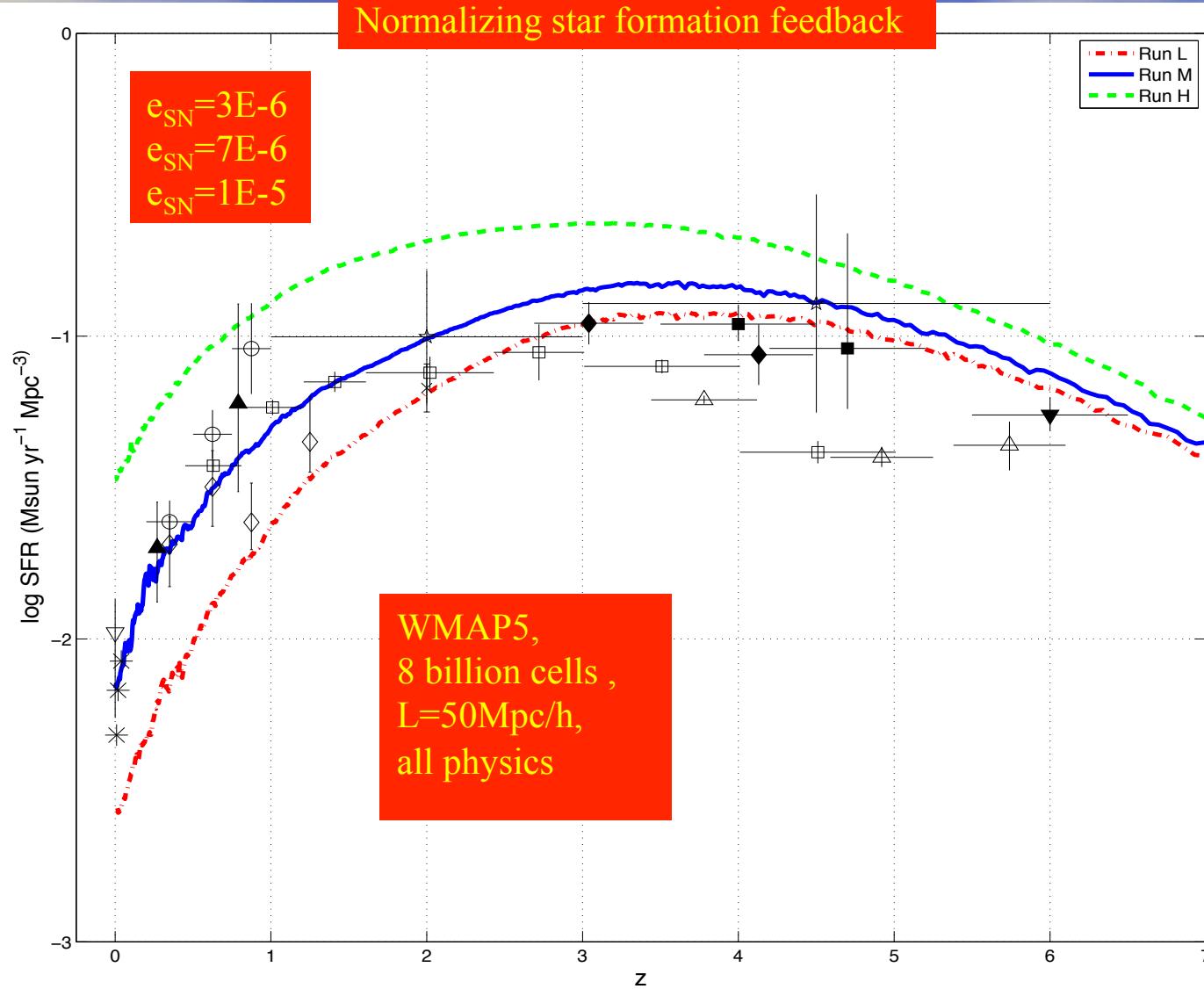
- ❖ Covers all space & contains most of the baryons
- ❖ Provides probes of physics/astrophysics
- ❖ Prerequisite to understanding galaxy formation, evolution and feedback processes

- ❖ There is a rich observational database:
  - Cosmological reionization
  - Lyman alpha forest
  - Optical absorption metal line systems
  - UV and X-ray forest
  - X-ray clusters of galaxies
  - soft X-ray background
  - Warm-Hot Intergalactic Medium (WHIM)
  - ...

# Cosmic Timeline in Standard Model

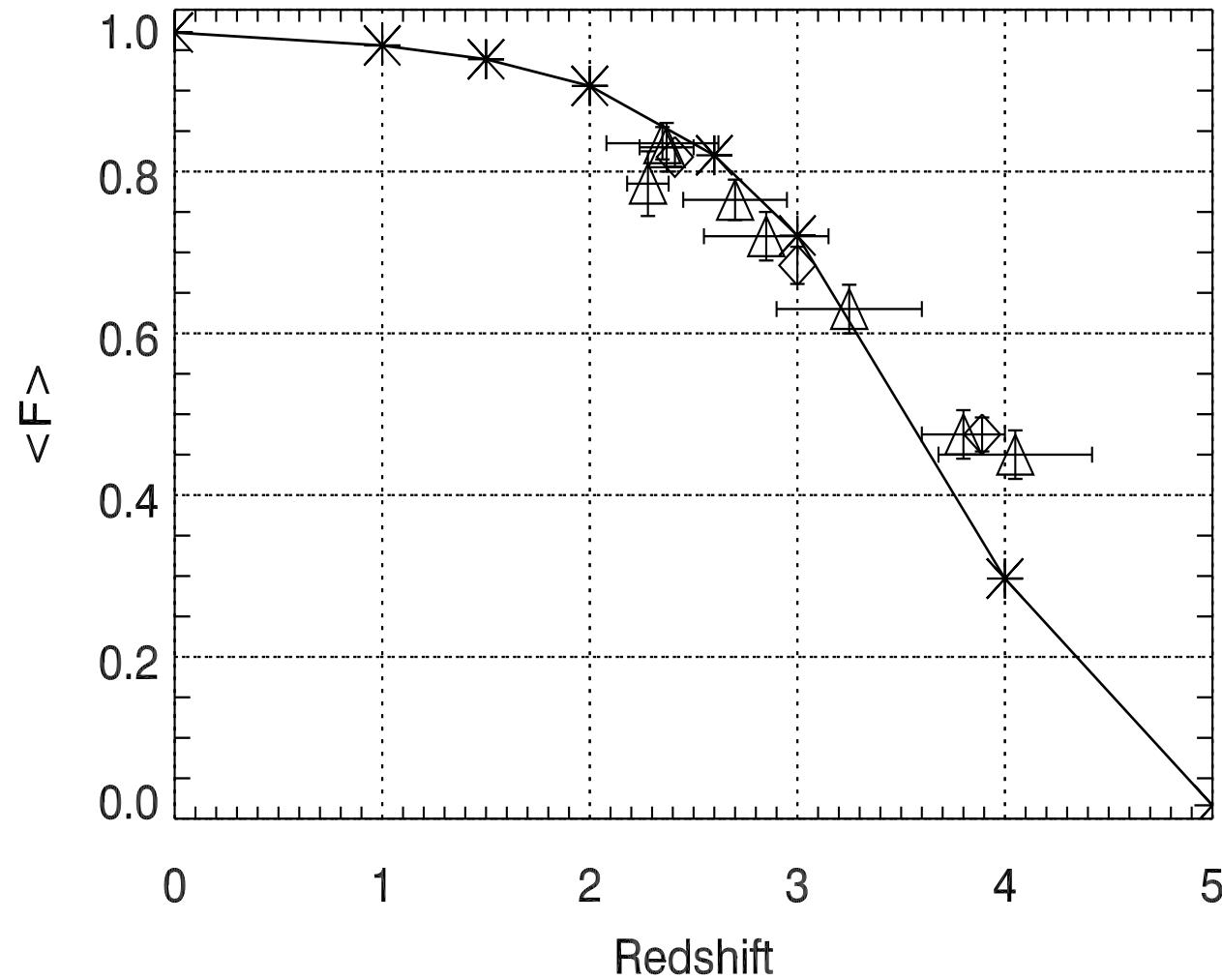


# Metal Enrichment History of the IGM



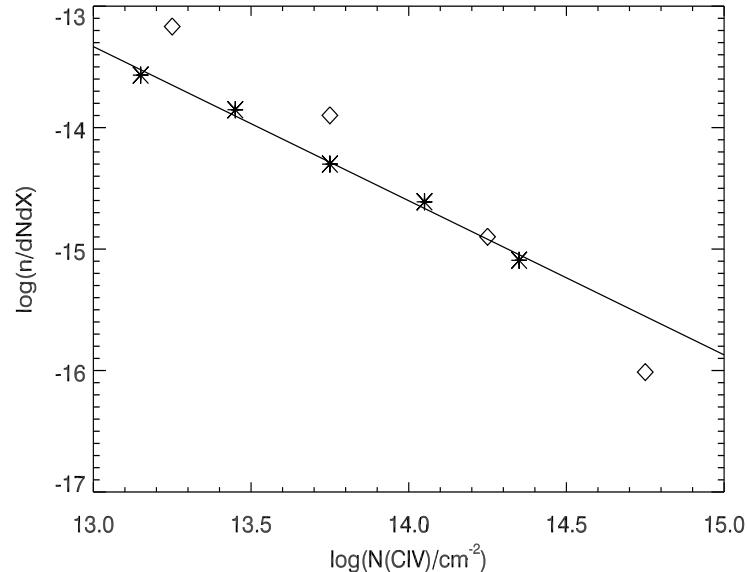
Cen & Chisari (2010, arXiv:1005.1451)

## Normalizing Radiation Background



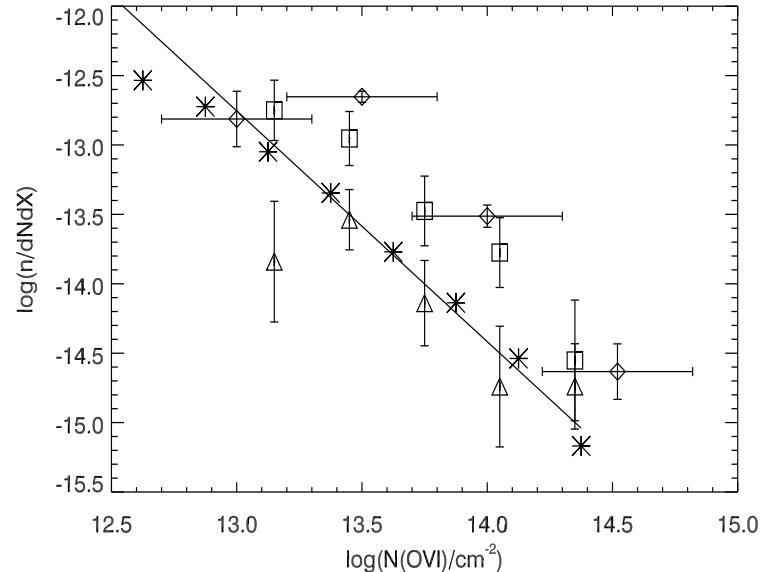
# CIV and OVI Column Density DF

CIV column density distribution



@z=2.6

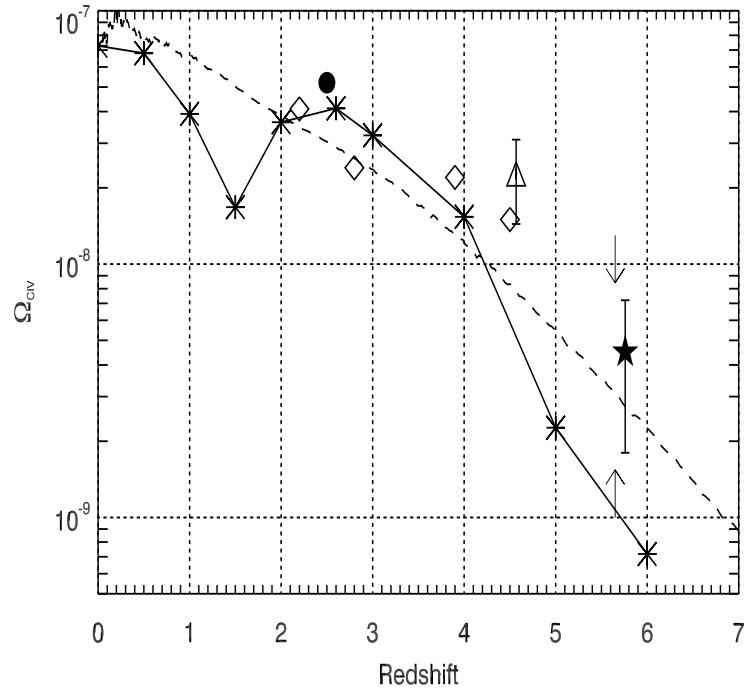
OVI column density distribution



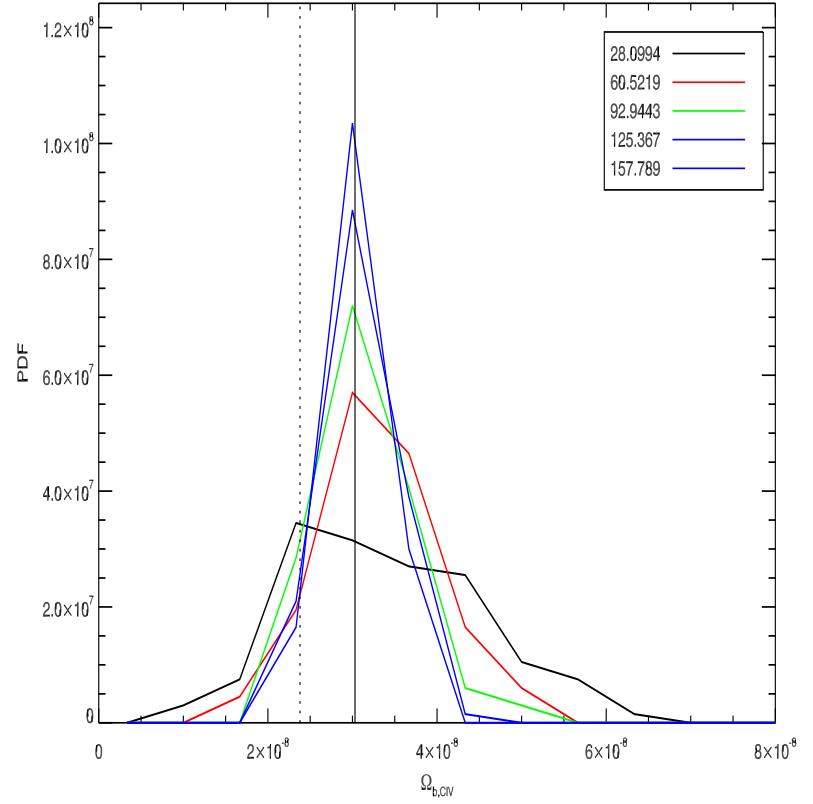
asterisks: Songaila (2001)  
diamonds: Ellison (2000)

diamonds: Bergeron (2005)  
squares: Carswell (2002)  
Triangles: Simcoe (2002)

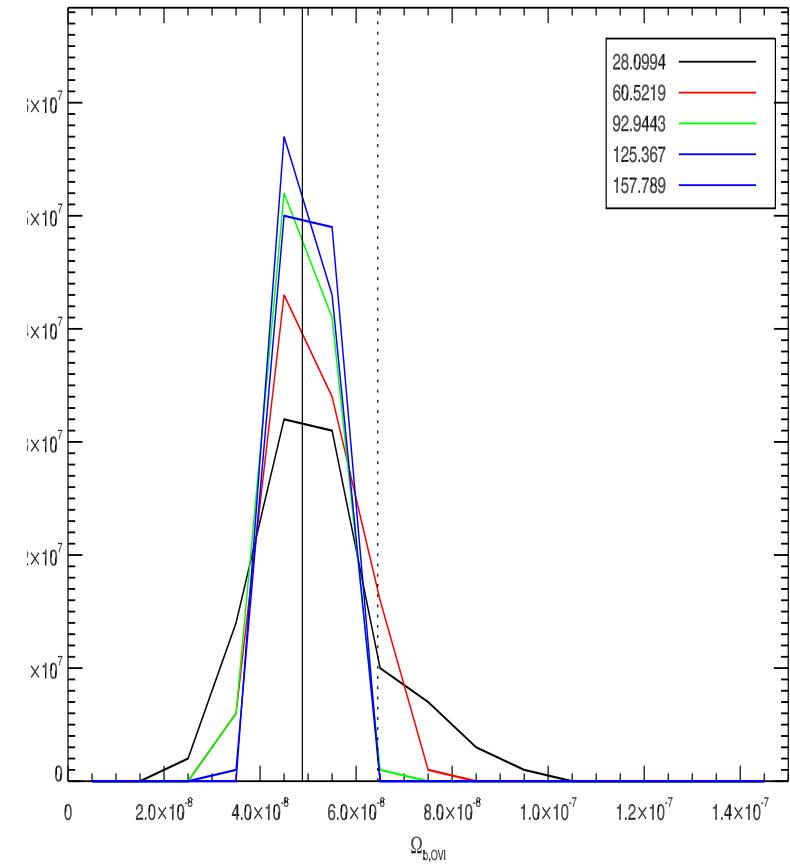
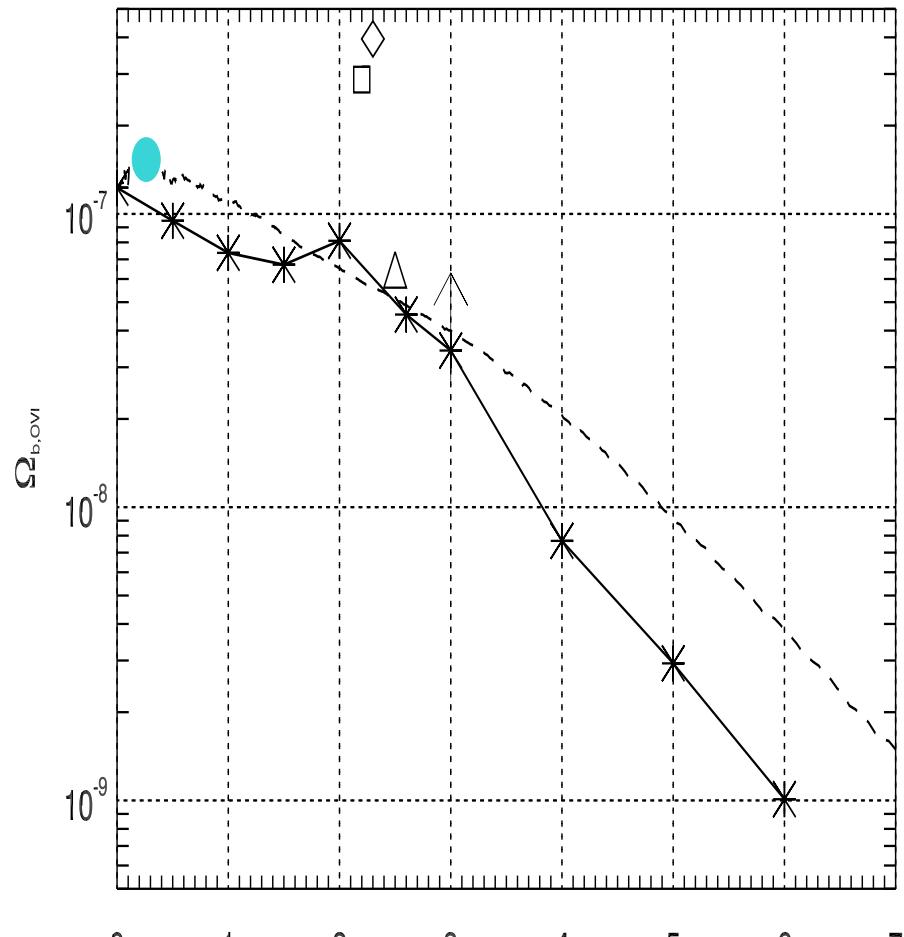
## Evolution of CIV density



diamonds: Songaila (2005)  
 arrows: limits by Becker (2009).  
 Triangle: Pettini (2003)  
 Star: Ryan-Weber (2009).  
 Circle: Simcoe (2008).

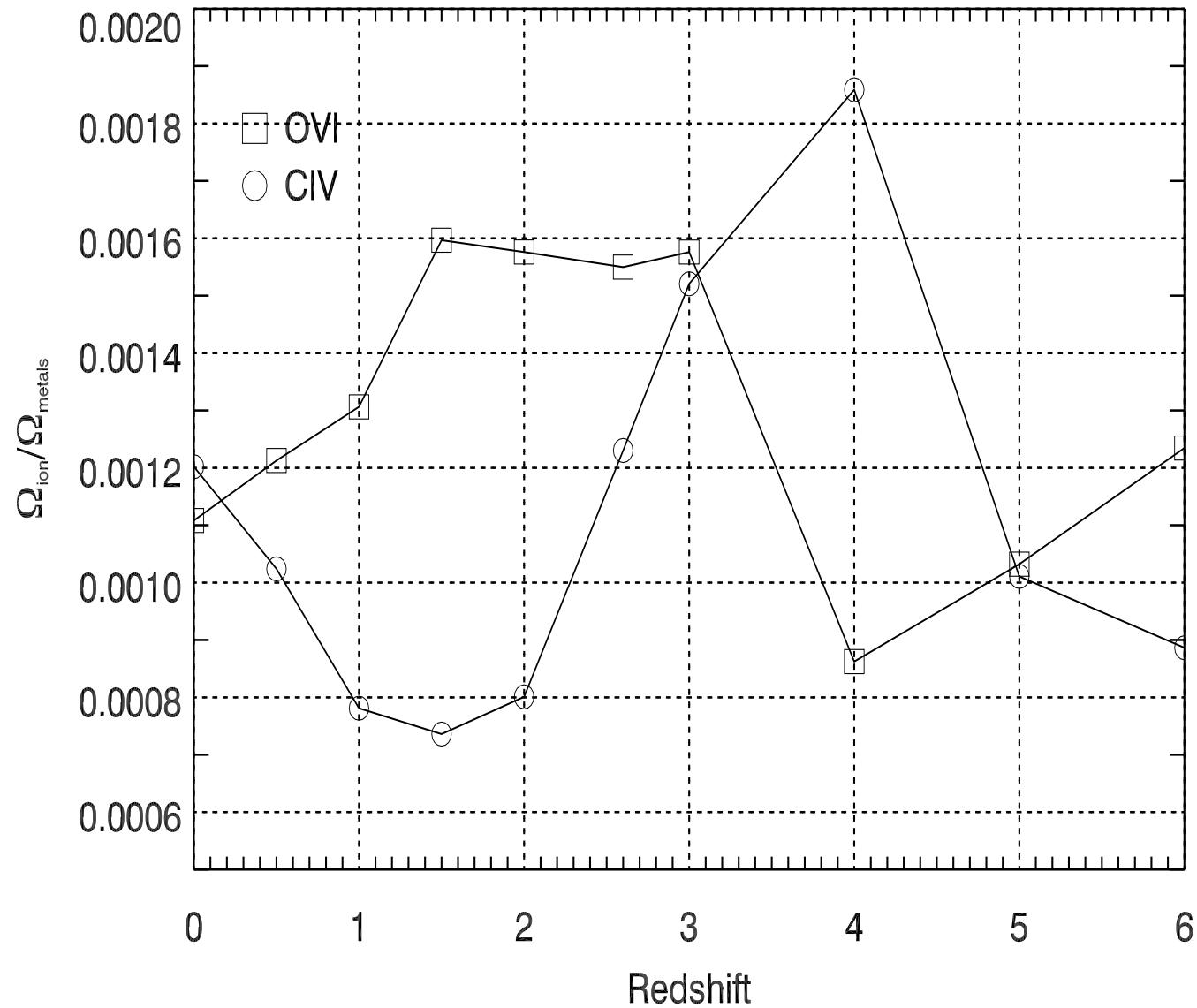


## Evolution of OVI density

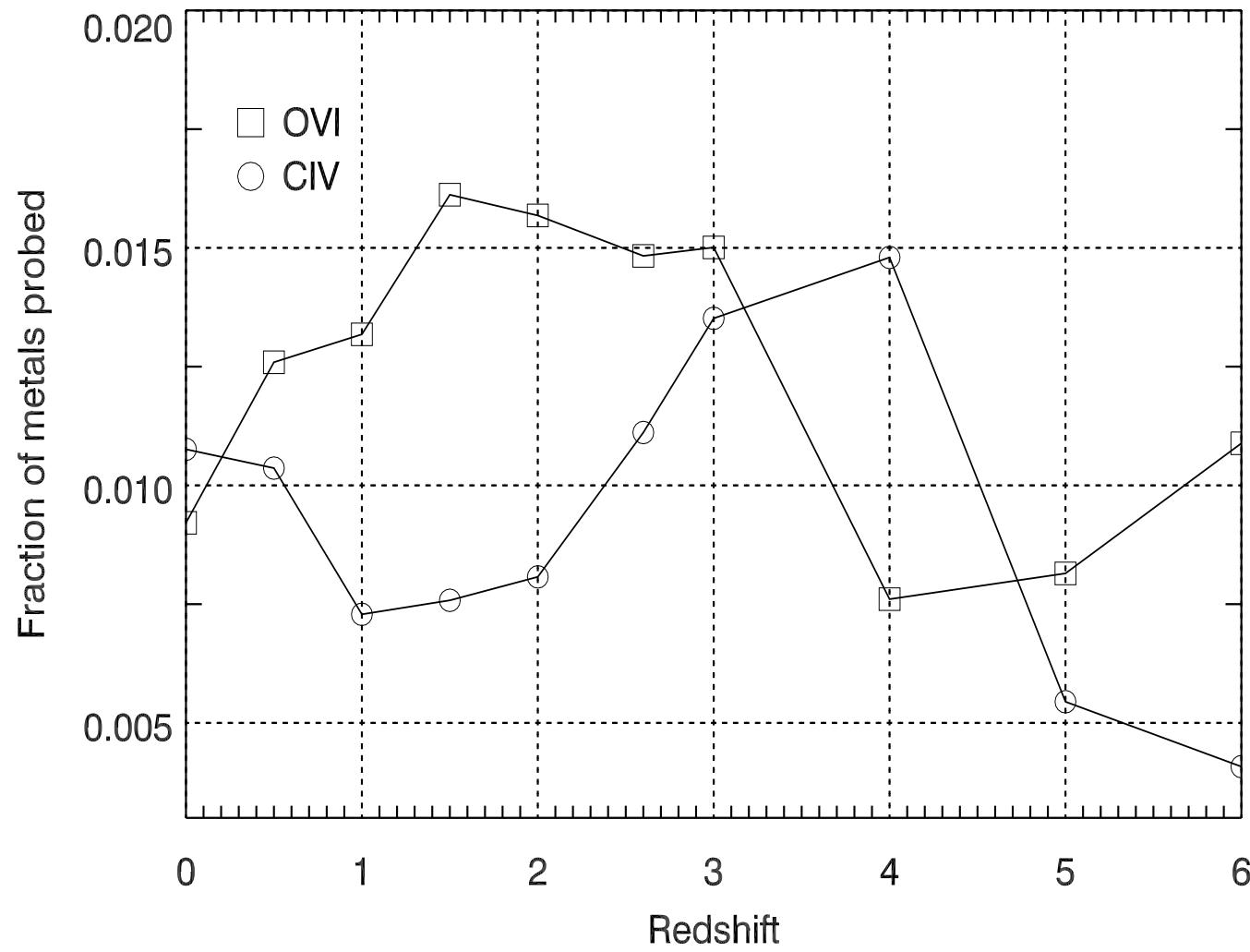


z      Square: Carswell 2002.  
 Diamond: Bergeron (2005).  
 Triangle: Simcoe (2002).  
 Arrow: lower limit by Frank (2008).  
 Oval: Danforth and Shull (2005)

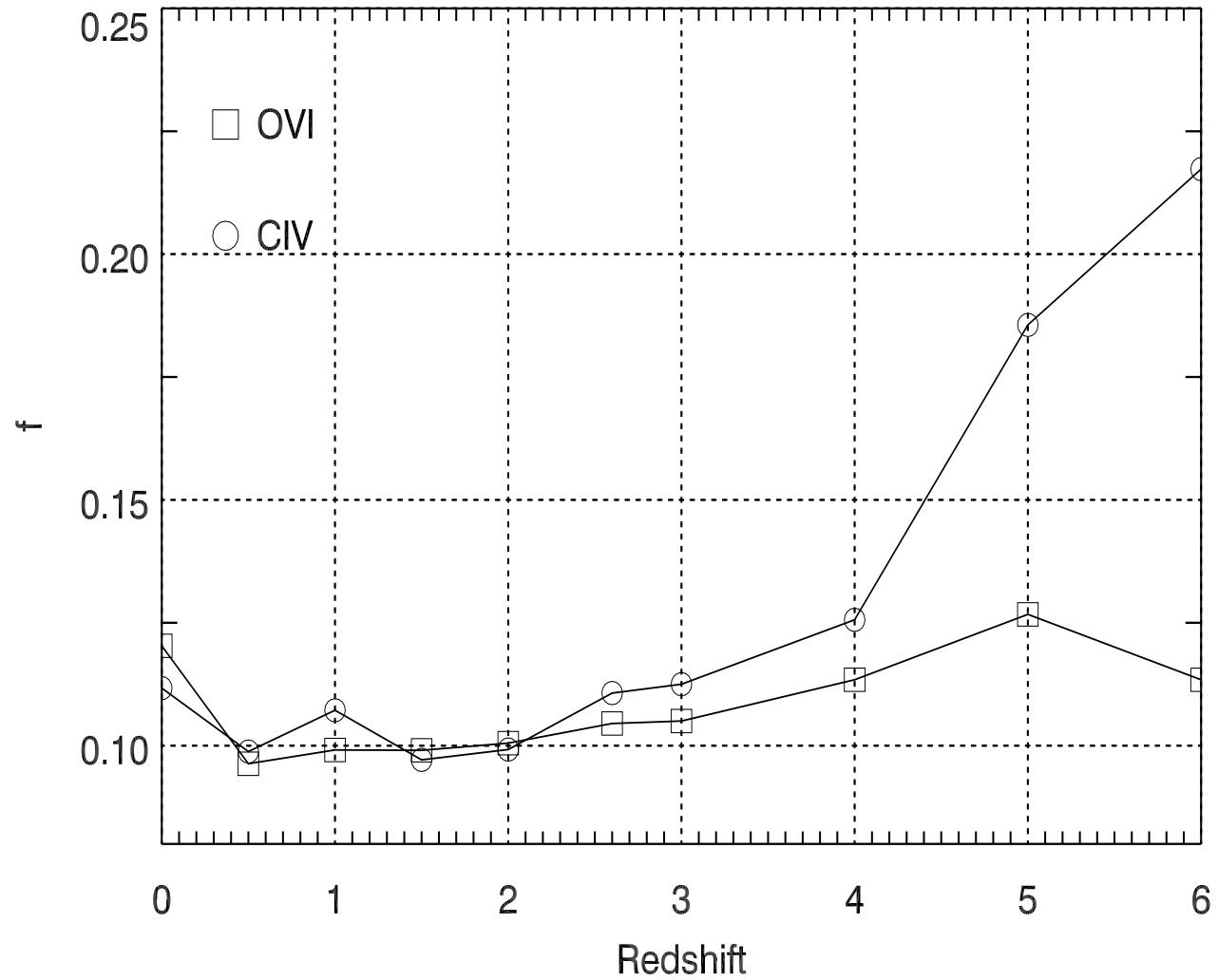
## Metals Fraction in CIV Lines



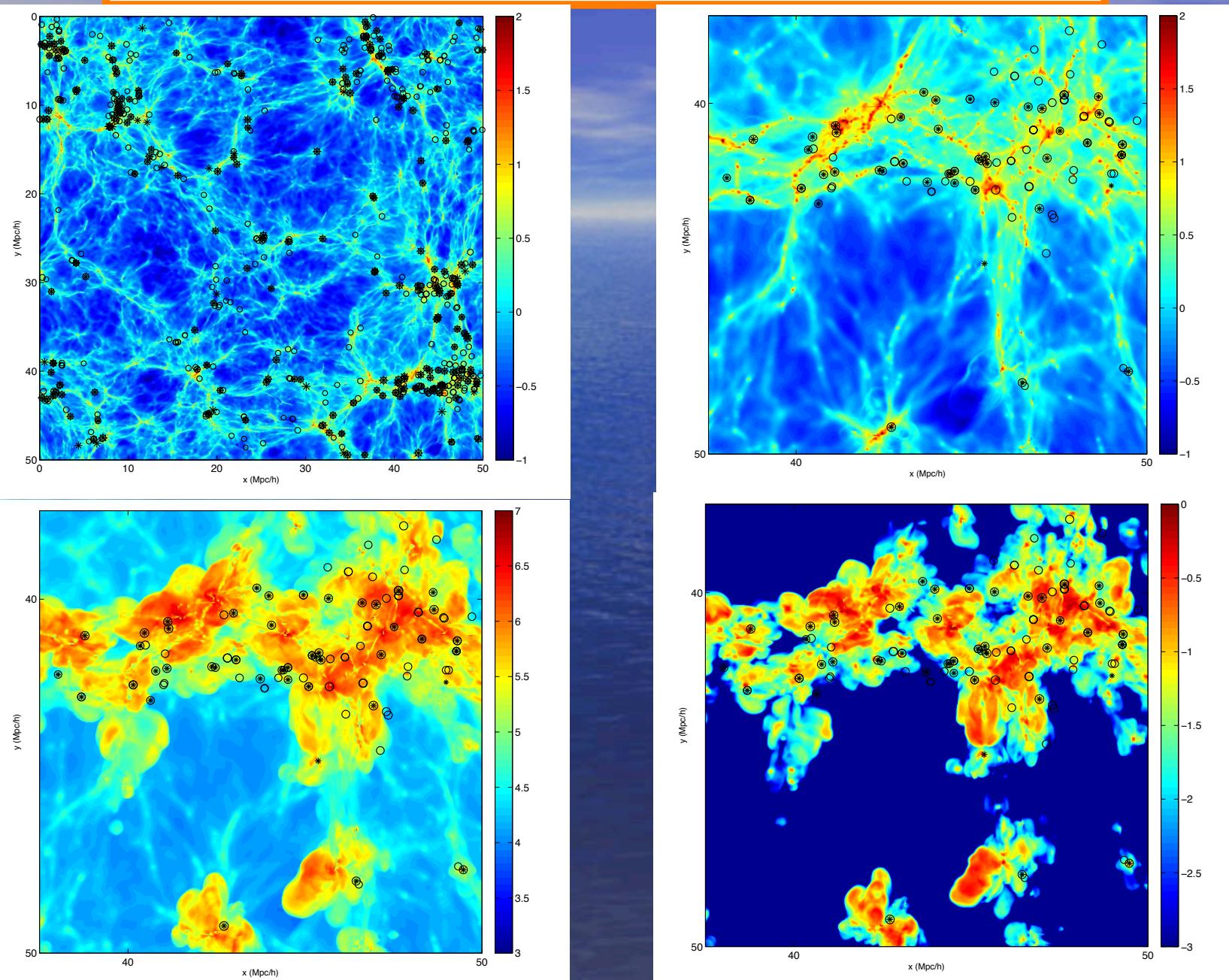
## Fraction of Metals Probed by CIV and OVI



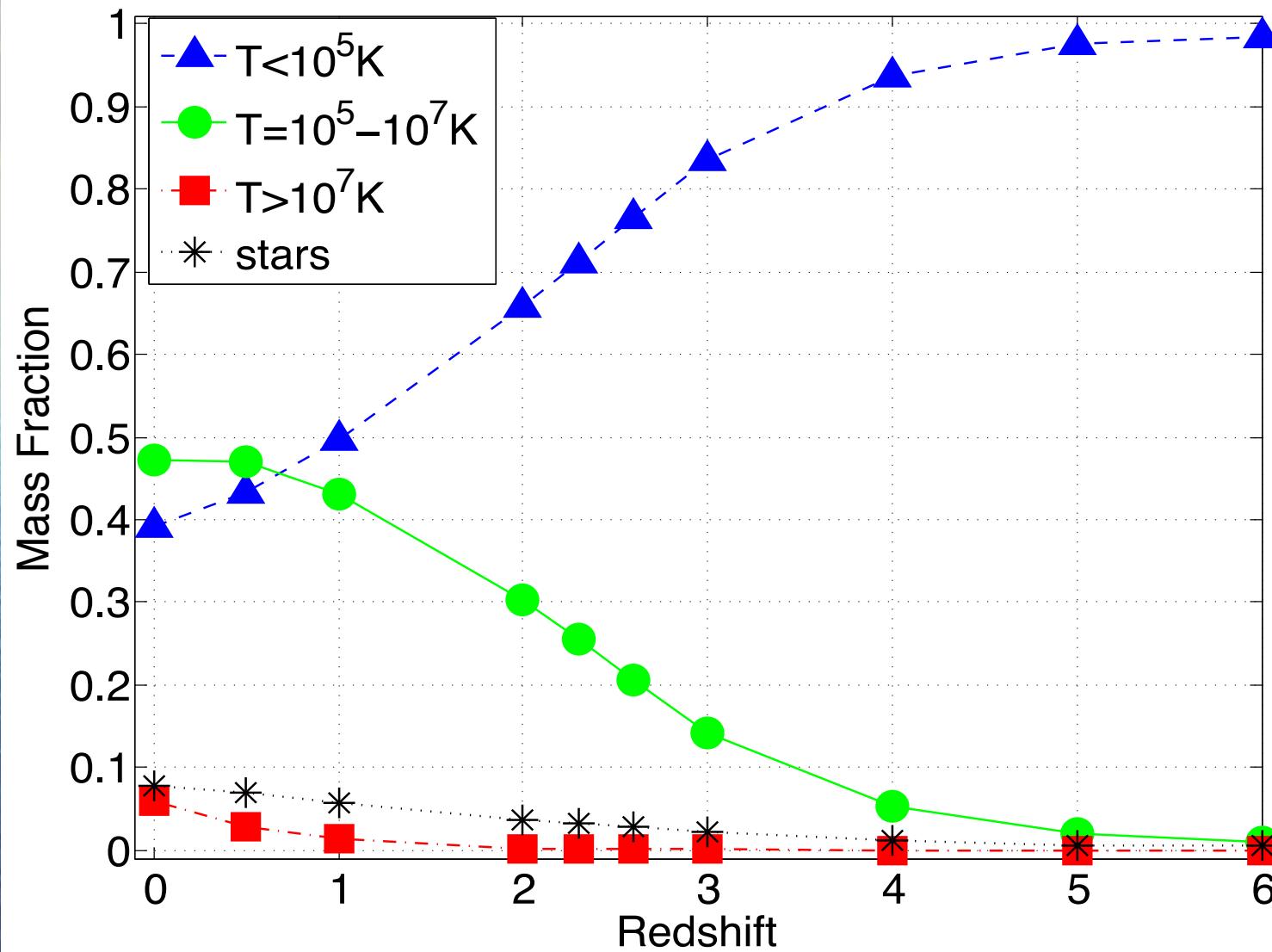
## Ratios CIV/C(tot) and OVI/O(tot)



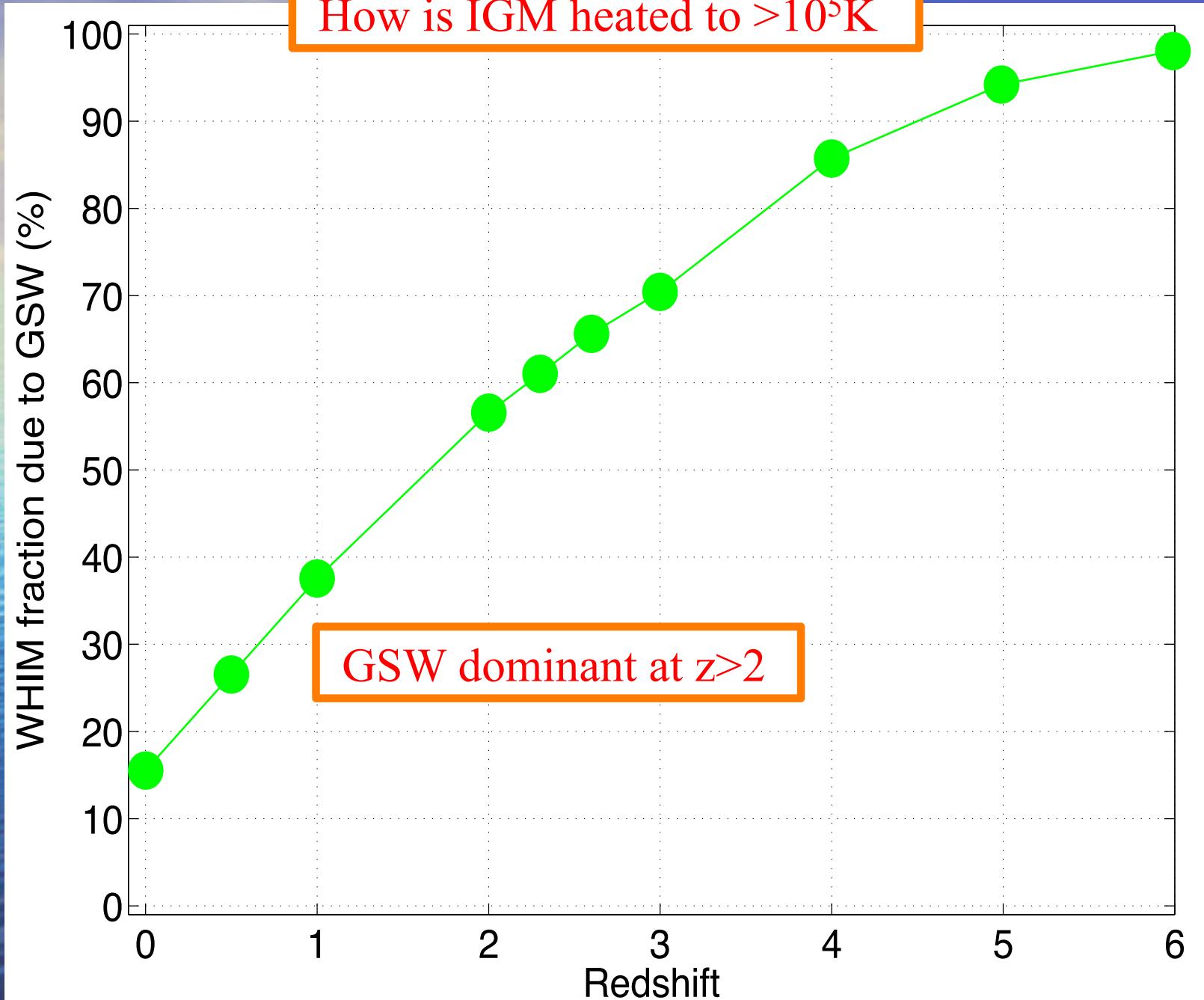
# Where are CIV and OVI absorption lines?



## Baryonic Components Mass - Evolution

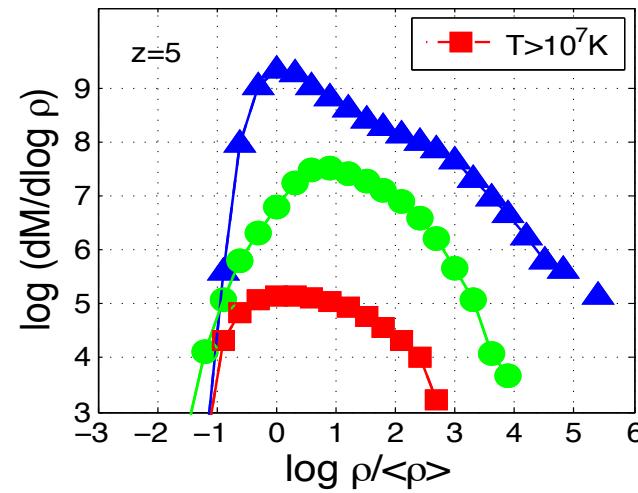
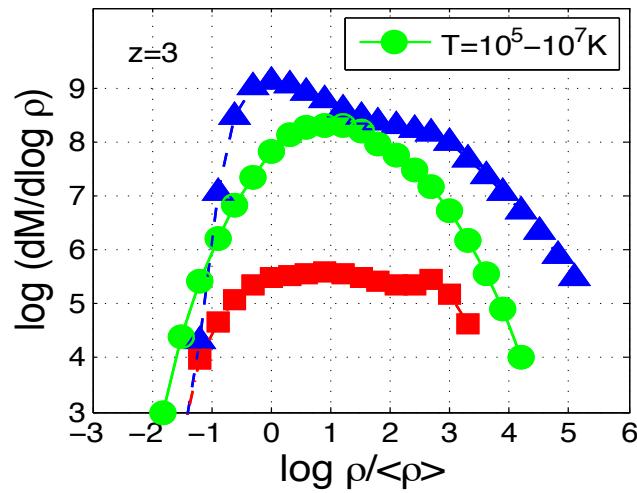
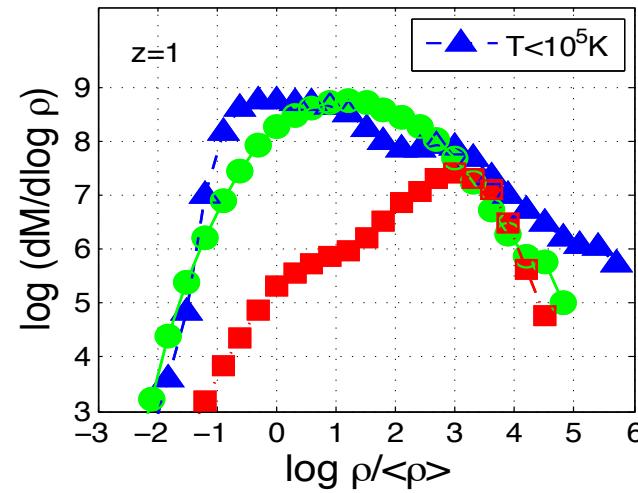
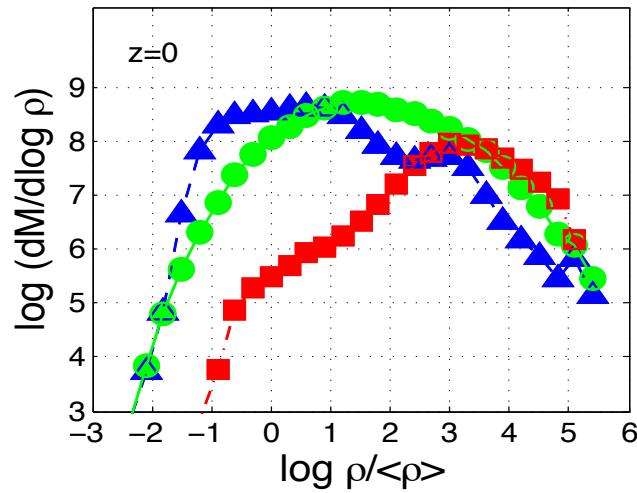


How is IGM heated to  $>10^5$ K

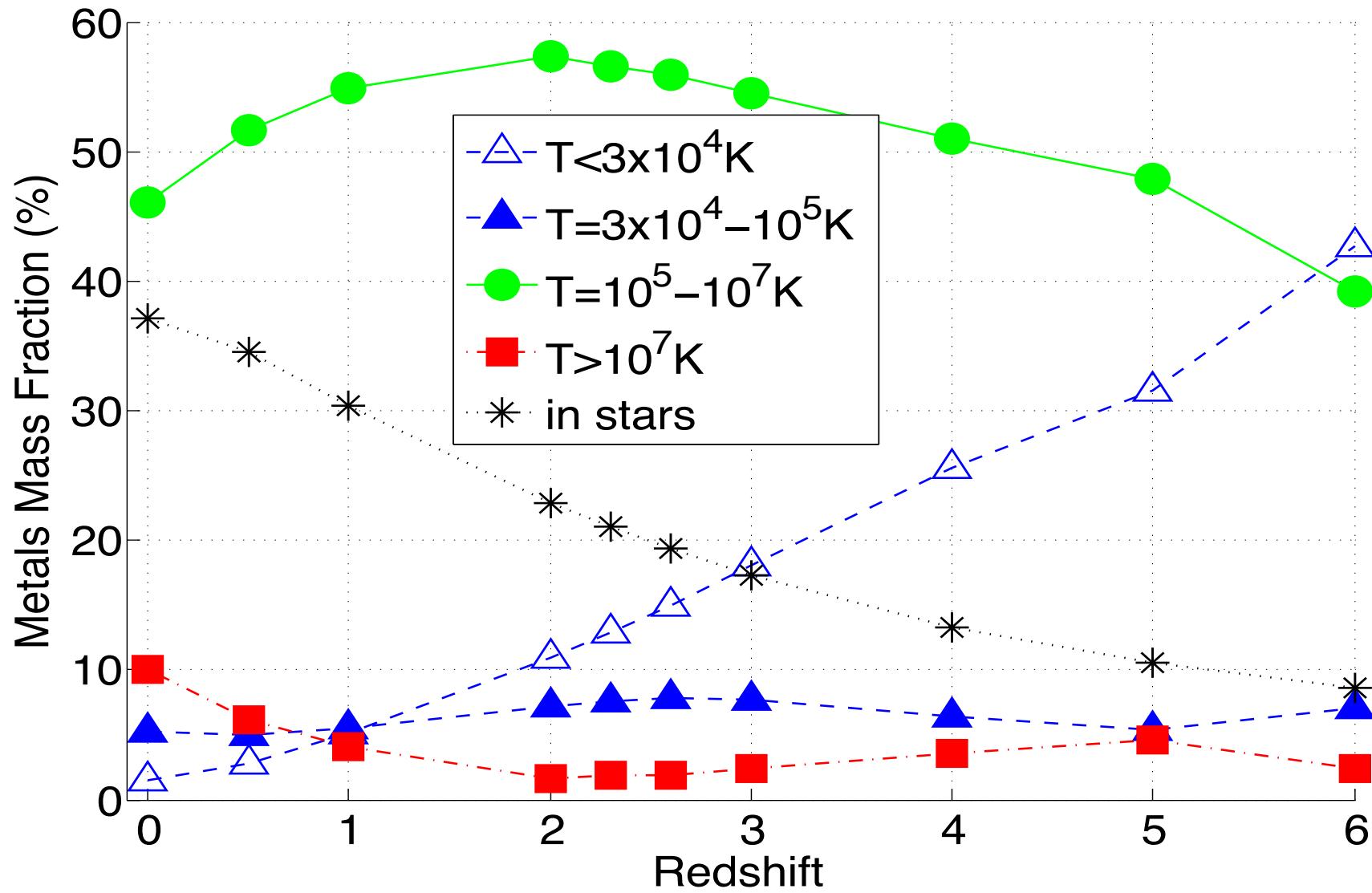


GSW dominant at  $z>2$

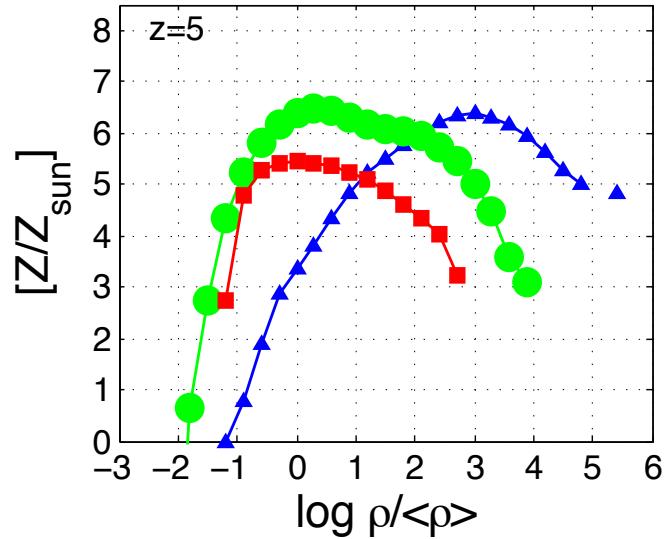
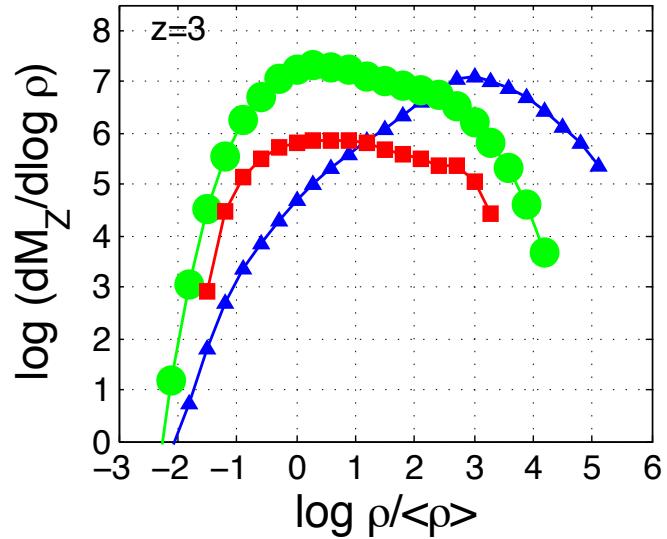
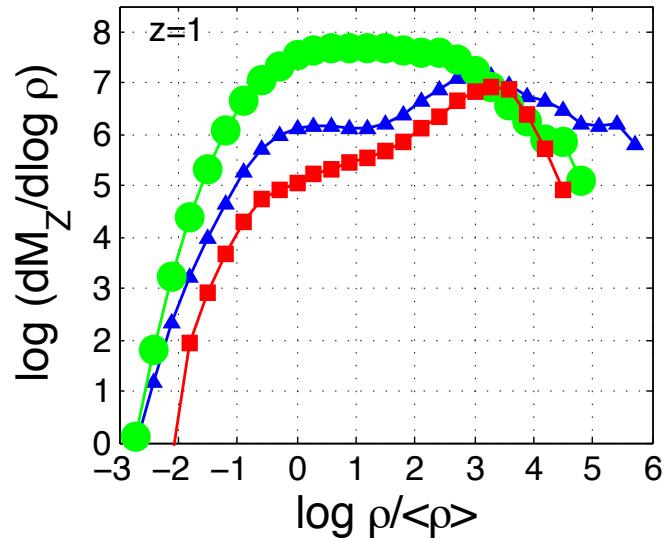
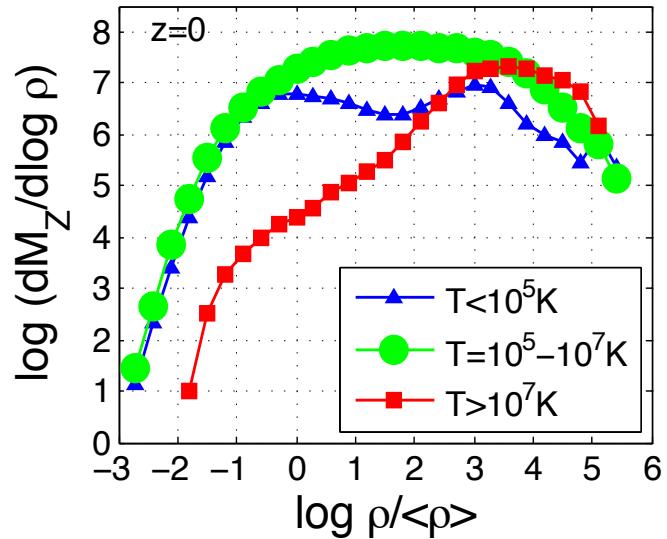
## IGM mass DF versus overdensity



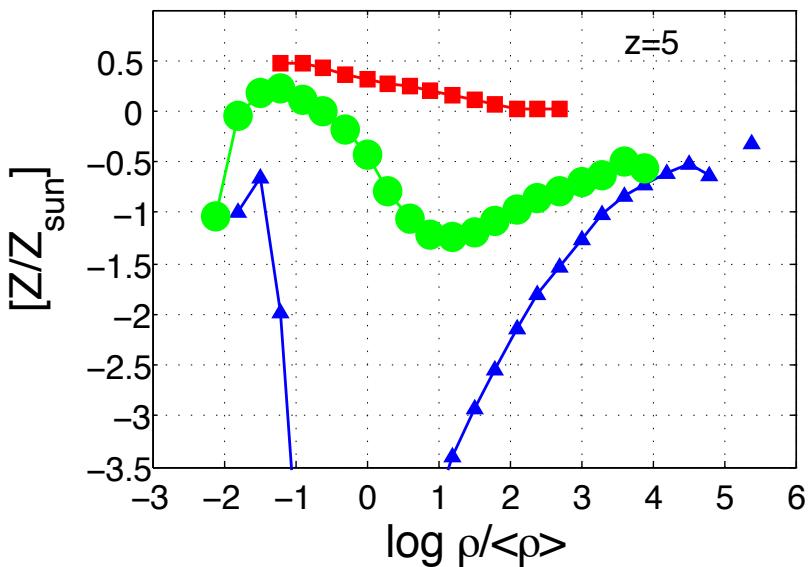
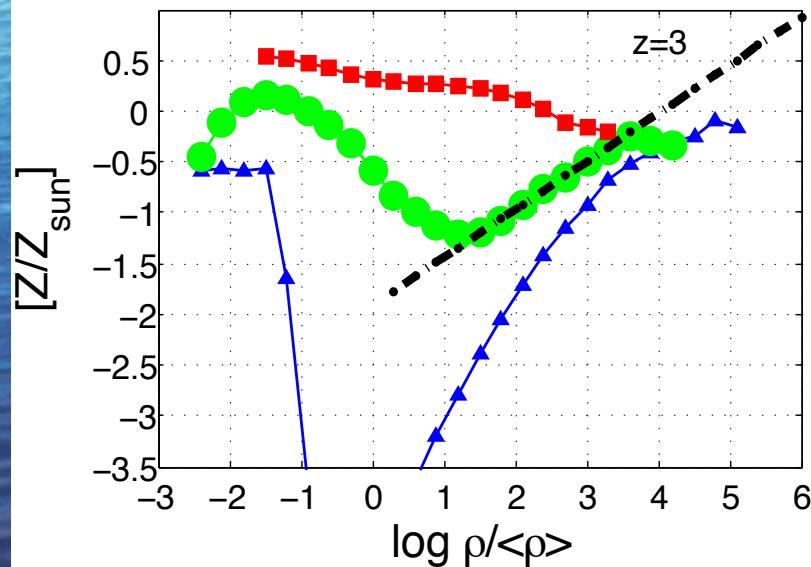
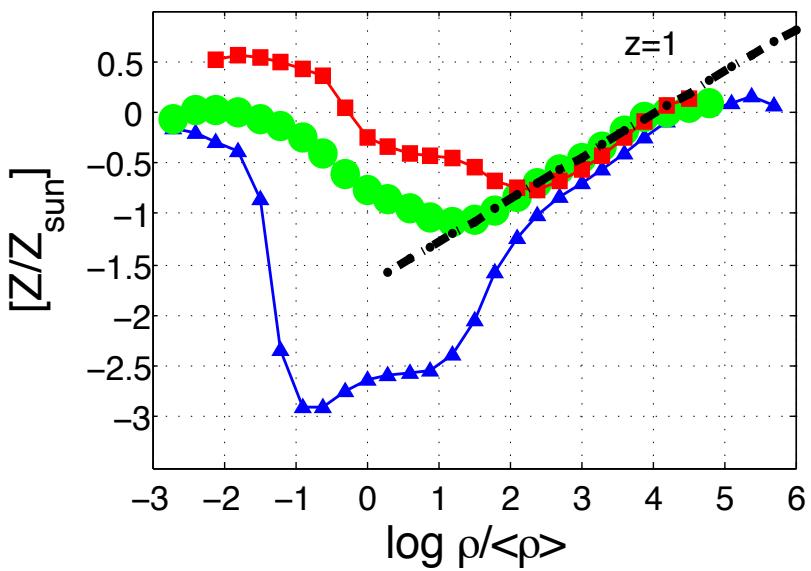
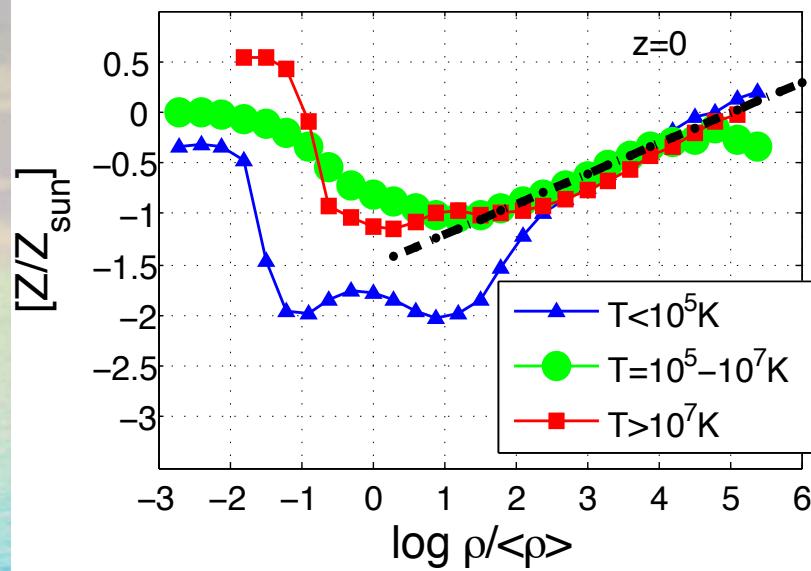
Where are the metals?



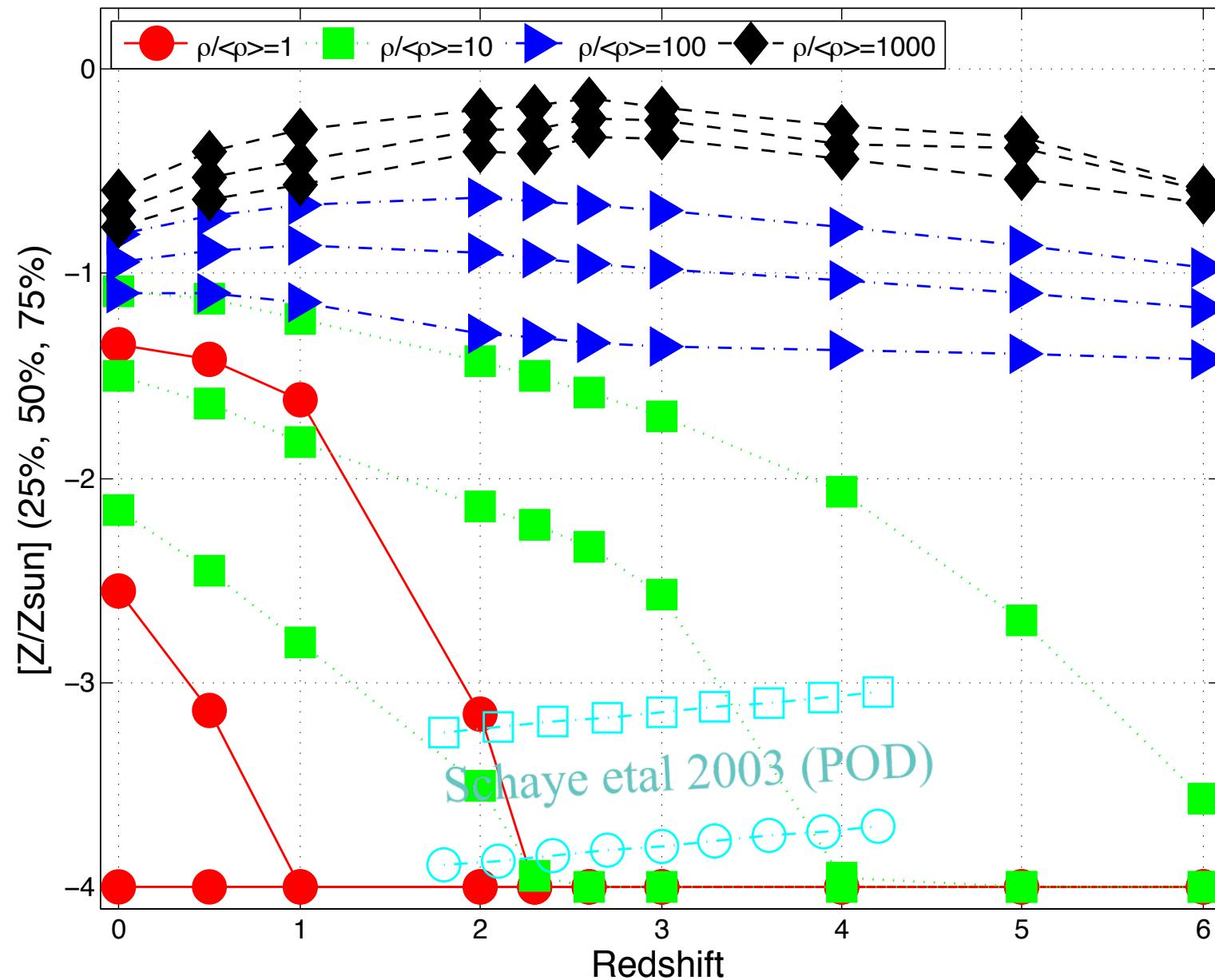
## Metals DF versus overdensity



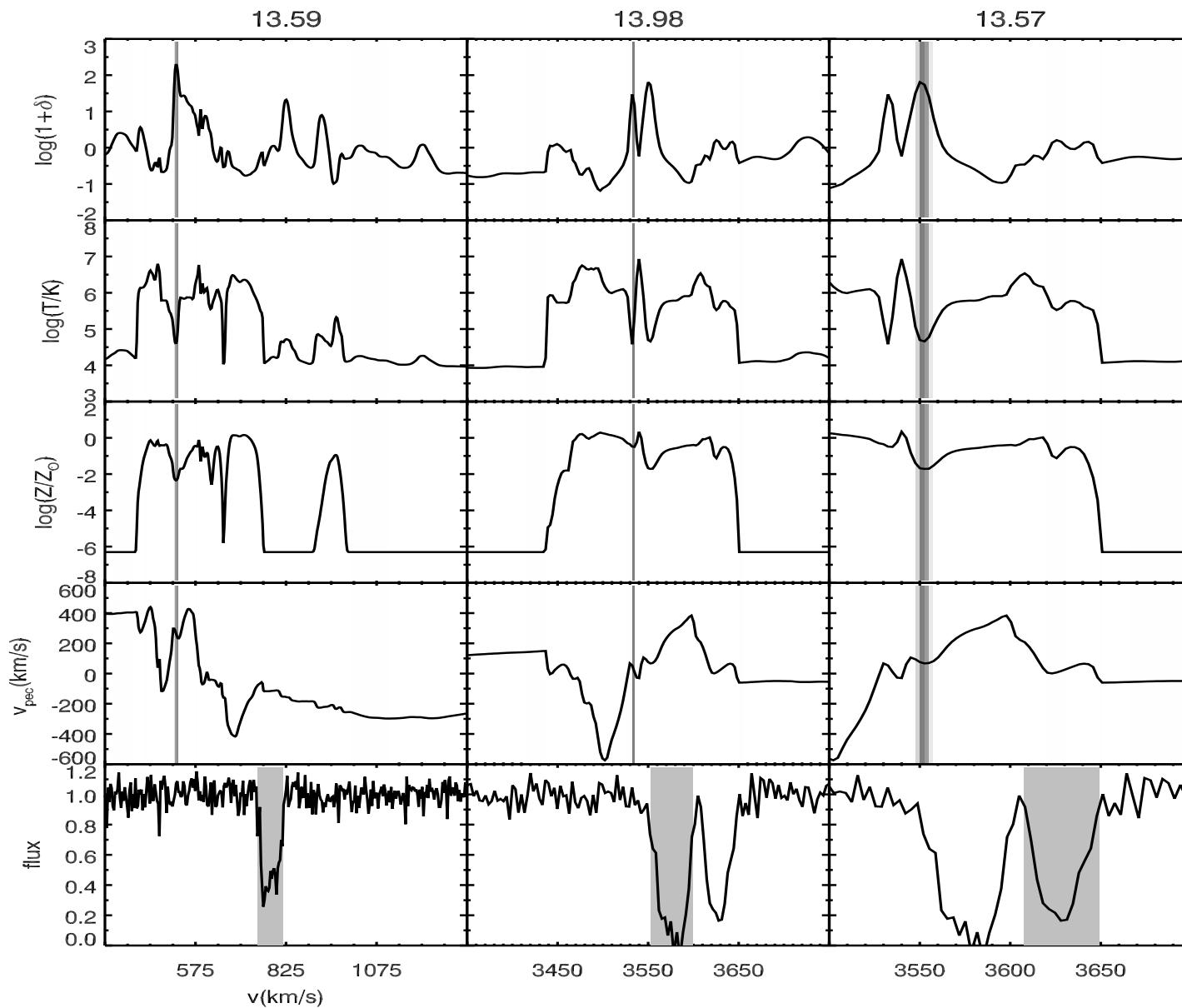
## Metallicity as a function of overdensity



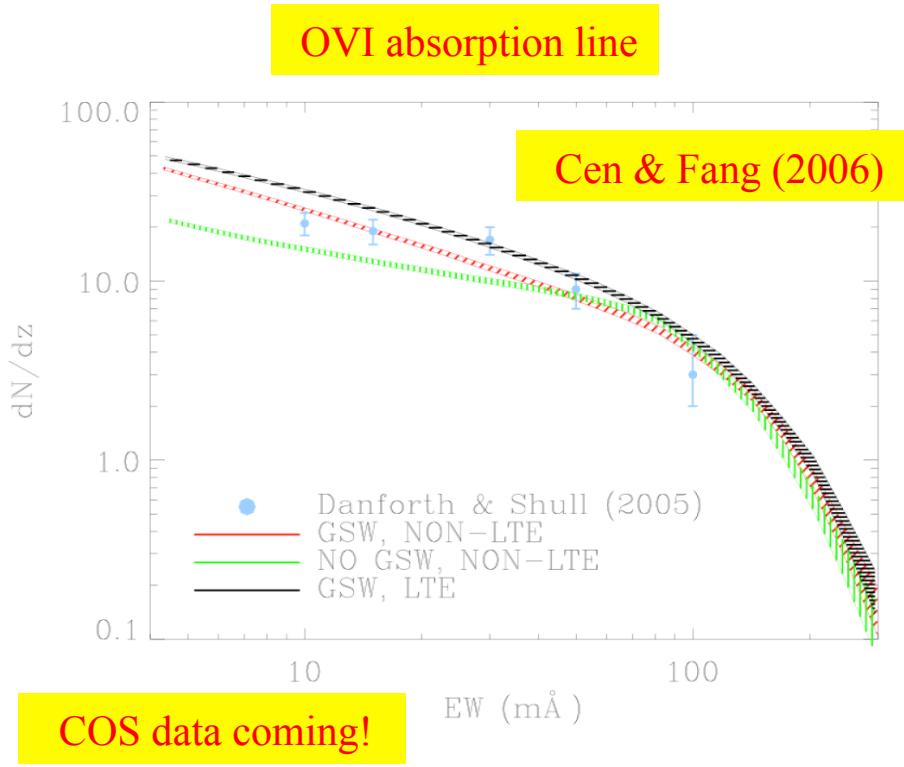
## Metallicity Evolution of IGM Components



# Structure of CIV line region and Separation from Ly $\alpha$ forest



## Probing WHIM and Xenia



OVII absorption along random LOS:

Fang et al 2001,2002 → no

Mathur et al 2003 → no

Nicastro et al 2005 → yes → no

Kaastra et al 2006 → no

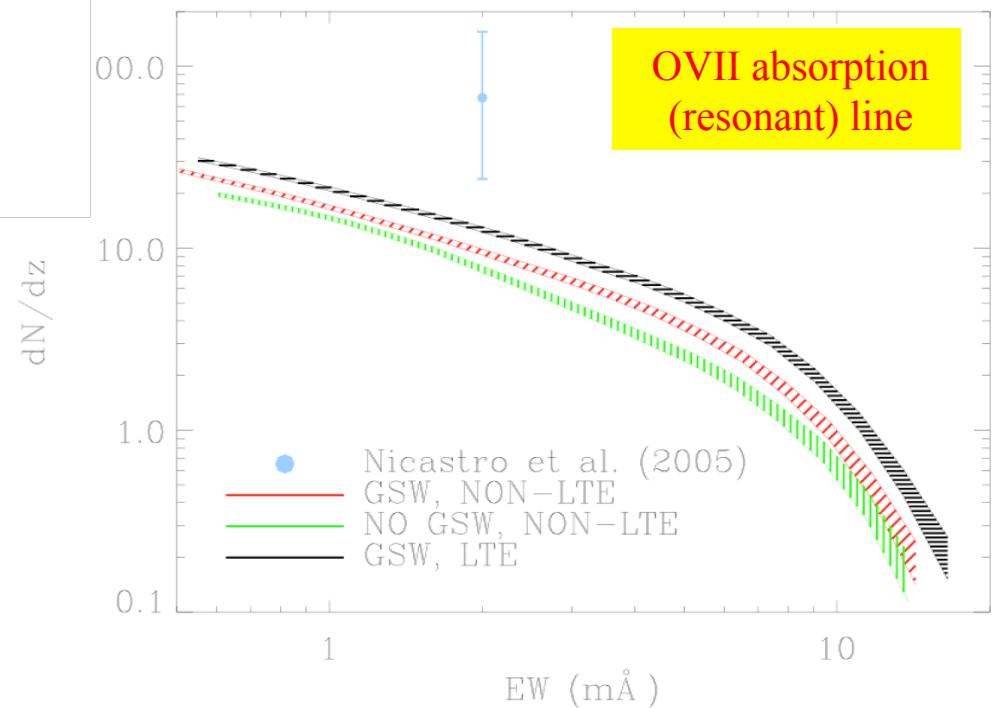
Steenbrugge et al 2006 → no

Rasmussen et al 2007 → no

NO

# WHAT to do?

*need Xenia to account for baryons*



OVII absorption targeted at known X-ray clusters/groups:

Fujimoto et al 2004: Virgo → yes

Takei et al 2007: Coma (X Comae) → yes

Buote et al 2009: Sculptor Wall → yes

YES

# Conclusions

- Star formation driven feedback in the context of LCDM model matches chemical contents of a broad range of cosmic systems (X-ray clusters, WHIM, galaxies, DLAs, metal line systems, Ly $\alpha$  forest)
- IGM metal enrichment is highly inhomogeneous
- CIV & OVI absorption lines are transients and probe only about 1% of total metals at any time that is a direct consequence of star formation feedback
- The “Missing Metals” at z=2-3 may be found in galactic superwind heated IGM at T>3E4K and overdensity of ~ a few (absorption for probing galaxy-IGM interaction?)
- Ly $\alpha$  forest with overdensity <= 1 is not significantly enriched (Z<-3)
- Need Xenia to account for missing baryons today